ARI The Bulletin of the Istanbul Technical University VOLUME 53, NUMBER 2
Communicated by Derin Orhon

Advances in Earthquake Risk Assessment and Hazard Reduction for Large Inventory of Structures with High Characteristic Variability

Oral Büyüköztürk and Oğuz Güneş
Department of Civil and Environmental Engineering,
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, U.S.A
(Received 30 June 2003)

Seismic risk assessment and hazard mitigation for urban infrastructures located in seismic regions is a challenge faced by many countries around the world, especially those with infrastructures known for their variability in seismic resistance and quality of construction. Two recent major earthquakes that hit the densely populated urban areas in Northwest Turkey resulted in a large-scale destruction and loss of life. Scientific studies indicate that the probability of occurrence of another severe and destructive earthquake along the North Anatolian Fault near Istanbul is quite high in the next thirty years. This situation presents a serious threat to the large building stock and their occupants, lifelines, and critical facilities in Istanbul and adjacent areas. The criticality of the situation is exacerbated by the fact that the existing structures in these areas are known to have high variability in their seismic resistance, which makes it difficult to estimate the potential losses in case of a major earthquake. Limited time and funds do not allow for a detailed evaluation of the entire inventory of structures according to seismic codes. Thus, there is an urgent need for a systematic strategy that will allow for a reliable assessment of the seismic hazard risk of existing structures through an effective and economical methodology. Prioritization of these structures according to their hazard risk, and implementation of the necessary mitigation measures are required. This paper presents the methodologies and advances in large-scale seismic risk evaluation and hazard reduction, and identifies the needs for further research.

Keywords: Earthquakes, structures, vulnerability, seismic risk, risk assessment, retrofit, advanced technologies.

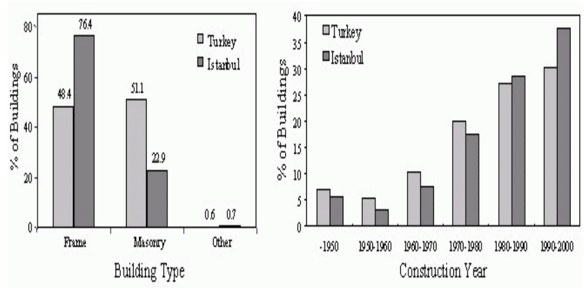
1. Introduction

Two recent major earthquakes that hit the densely populated urban areas in Northwest Turkey (Aug. 17, 1999 Kocaeli Earthquake, Mw=7.4, and Nov. 12, 1999 Duzce Earthquake, Mw=7.2) resulted in a large-scale destruction and loss of life. Scientific studies indicate that the probability of occurrence of another severe and destructive earthquake along the North Anatolian Fault, near Istanbul, is $62 \pm 15\%$ within the next 30 years [1]. This presents a serious threat to the large building stock and their occupants, lifelines, and critical facilities in Istanbul and adjacent areas. Furthermore, existing structures in these areas are known to have high variability in their seismic resistance, making it difficult to estimate the potential losses in case of a major earthquake. Limited time and funds do not allow for detailed evaluation of the whole inventory of structures according to the "Specification for Structures to be Built in Disaster Areas" [2] hereafter referred to as the Turkish Earthquake Code. Under these circumstances, there is an urgent need for a systematic strategy that will allow for a reliable assessment of the seismic hazard risk of existing structures through an effective and economical methodology. Prioritization of these structures according to their hazard risk, and implementation of the necessary mitigation measures are required. A general outline of such a strategy and associated technical, administrative, and research needs were summarized in a recent report by the National Earthquake Counsel of Turkey [3]. As stated in this report, the risk assessment and mitigation strategy to be developed must benefit from the existing worldwide knowledge and experience in this area as much as possible, however, this knowledge and expertise must be adapted and further developed to meet the conditions specific to Turkey. This paper presents the methodologies and recent advances in large-scale seismic risk evaluation and hazard reduction, with emphasis on large inventory of structures with high characteristic variability in their seismic resistance.

2. Problem Statement and Research Needs

According to the State Statistics Institute (DIE) of Turkey, the total number of buildings in Istanbul is around 870,000, approximately 11% of the total number of buildings in Turkey [4]. Including those in the adjacent seismic regions, this number reaches well over one million. More than three quarters of the buildings in the Istanbul region are frame type of buildings that were constructed within the last thirty years as shown in Fig. 1.a and b, respectively. Although this raises some optimism about the condition of the building stock considering that a modern seismic code was enforced in 1975 [5], there are concerns regarding the material and construction quality, and problems with seismic detailing. In addition to the building stock, the region contains a fairly developed network of transportation systems, utility systems, and a large number of critical facilities such as army installations and hazardous material storage sites. Ensuring the safety of the structural inventory and their occupants against a major earthquake is an enormous challenge given the time frame and available economic resources. However, it is essential that an optimized systematic effort must be given to minimize the potential losses to the possible extent. The priority needs for seismic hazard reduction of the building stock in Istanbul and other seismic regions include:

- Seismic demand characterization through hazard analysis and microzonation,
- Vulnerability and risk assessment of the existing infrastructure and population for a design earthquake,
- Rapid identification and prioritization of the structures with insufficient seismic resistance,
- Seismic retrofitting of deficient structures using efficient and cost effective techniques,
- Development and enforcement of appropriate policies on land use, seismic design, retrofit design, and construction,
- Educating the public, students, and practitioners at various levels about seismic risks and loss reduction issues.



(a) (b)

Figure 1. Distribution of the building stocks in Istanbul and Turkey by type and age (a) distribution or buildings by type (b) distribution of buildings by age.

In conducting the requirements of these priority needs, a coordinated effort by several state agencies is essential in order to gather the necessary data and information regarding the faults, seismicity, geology, available structural inventory and population density.

3. Seismic Risk Assessment and Loss Estimation

Seismic risk assessment and loss estimation is an essential first step to seismic hazard reduction for a large structural inventory. Knowing the seismic risk and potential losses allows for proper budgetary planning, raising public awareness, assessment and allocation of the necessary manpower for mitigation and disaster management operations, educating the public and professionals on preparedness and mitigation, and prioritization of retrofit applications [6]. Components of seismic risk assessment and loss estimation are (1) Hazard analysis; (2) Local site effects (microzonation); (3) Exposure information (structural inventory); (4) Vulnerability analysis; (5) Estimation of risk and loss [7-10]. These components are briefly described in the following subsections.

3.1. Hazard Analysis

Hazard analysis is the process of quantitatively estimating the ground motion at a site or region of interest based on the characteristics of surrounding seismic sources. This study falls primarily within the disciplines of geology and seismology

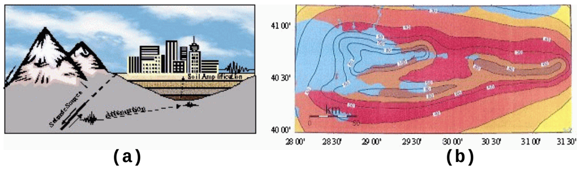


Figure 2. Illustration of hazard analysis and resulting hazard map (a) graphical illustration of hazard analysis (b) a hazard map of Marmara region (Frankel et al., 1999).

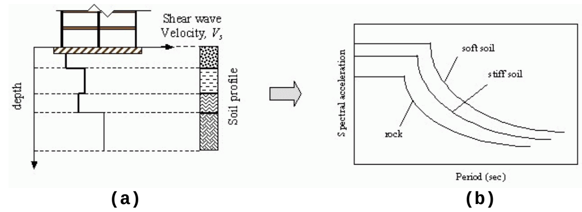


Figure 3. Site-specific response spectra based on soil shear wave velocity (a) subsurface soil profile and shear wave velocity (b) response spectra for different soil conditions.

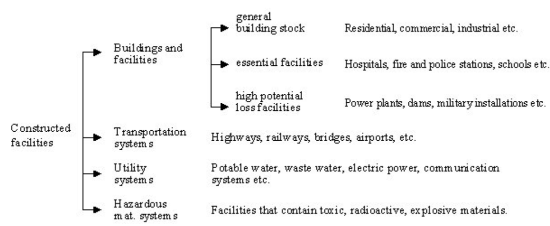


Figure 4. A structural inventory classification system (ATC, 1985; FEMA, 1999).

with input from civil engineering [11]. In this respect, the term seismic hazard has a technical meaning restricted to the behavior of the ground, apart from any effects on the built environment. The basic methodology of hazard analysis is comprised of source modeling, wave attenuation, and local ground amplification, which are graphically illustrated in Fig. 2.a. Seismic hazard may be analyzed deterministically for a scenario earthquake, probabilistically, which explicitly considers the earthquake size, location, and time of occurrence, or a stochastic approach may be taken [12, 13]. Probabilistic assessment of seismic hazard involves determining either the probability of exceeding a specified ground motion, or the ground motion that has a specified probability of being exceeded over a particular time period. Accordingly, output of the hazard analysis is either a curve showing the exceedance probabilities of various ground motions at a site, or a hazard map that shows the estimated magnitude distribution of ground motion that has a specific exceedance probability over a specified time period at a region. Such a hazard map developed by [14] is shown in Fig. 2.b for demonstration. By developing the hazard maps in the GIS (Geographical Information System) format, prediction of local ground motion parameters can be automated for designers' use [15].

3.2. Local Site Effects and Microzonation

Local geologic and soil conditions can significantly influence ground motion characteristics such as magnitude, frequency content, and duration [12, 13]. Accurate assessment of local site conditions is essential in determining the ground motion parameters as well as the potential of liquefaction and ground failure. Consideration of the local site condition results in the development of a site-specific response spectrum to be used in the structural analysis and design. Fig. 3.b shows the typical response spectra for different soil conditions, which are determined based on the average soil shear wave velocity as illustrated in Fig. 3.a. Seismic design codes including the Turkish Earthquake Code [2] and International Building Code [16] classify soils into groups according to their properties including strength, penetration resistance, and shear wave velocity. Measuring these properties over a dense grid, and combining with hazard analysis, a detailed soil map can be developed that reveals not only the soil parameters required to obtain site-specific response spectra, but also the potential of liquefaction and ground motion. The process of developing such detailed maps is called microzonation.

3.3. Exposure Information

Exposure is the value of the structures and contents, business interruption, lives and other valuables that may lead to a potential loss in a seismic event. Depending on the scope of the risk

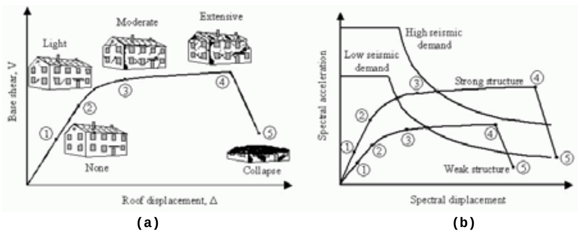


Figure 5. Structural vulnerability and damage states for various levels of seismic demand (a) damage states shown on V-D curve (b) damage levels based on seismic demand.

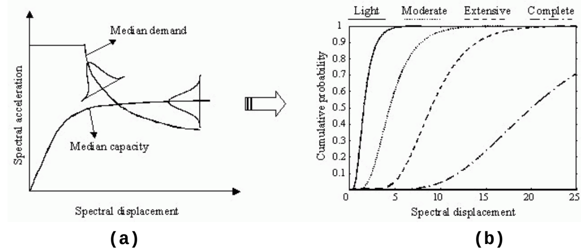


Figure 6. Uncertainties in seismic performance and use of fragility curves (a) uncertainities in seismic capacity and demand (b) fragility curves for various damage states.

assessment study, exposure may include a single building with its occupants and contents, or may include all constructed facilities in a region including all buildings with their occupants and contents, lifelines, and utility systems. Building exposure information for a region requires a standard systematic inventory system that classifies the structures according to their type, occupancy, and function so that realistic estimates of seismic risk and loss can be made. Such an inventory data collection and classification system was developed for California and was reported in ATC-13 [17]. This system, which was also utilized in the HAZUS Earthquake Loss Estimation Methodology and Software [15], is summarized in Fig. 4. A similar inventory system can be adapted for building the exposure information in seismic regions of Turkey.

3.4. Vulnerability Analysis

Vulnerability can simply be defined as the sensitivity of the exposure to seismic hazard(s). The vulnerability of an element is usually expressed as a percentage loss (or as a value between zero and one) for a given hazard severity level [7]. In a large number of elements, like building stocks, vulnerability may be defined in terms of the damage potential to a class of similar structures subjected to a given seismic hazard. Vulnerability analysis reveals the damageability of the structure(s) under varying intensity or magnitudes of ground motion. Multiple damage states are typically considered in the analysis. Fig. 5.a shows the damage states of a building based on the applied base shear, which can be determined as a function of the seismic demand. The roof displacement - base shear curve, also called the capacity curve, shown in this figure represents the nonlinear behavior of a building under increasing load or displacement demand. The damage state of the building varies between none to collapse under increasing levels of demand, which is graphically illustrated in Fig. 5.a. A relatively more convenient representation of the damage states is provided in Fig. 5.b by overlaying both building capacity and seismic demand curves on a different set of axes showing spectral displacement vs. spectral acceleration. Two different capacity and seismic demand curves are shown in the figure. Intersection of the capacity and demand curves represents the damage state likely to be experienced by the structure. As can be seen from the figure, the strong structure is likely to suffer from light to moderate damage due to the low seismic demand, and moderate to extensive damage due to the high seismic demand. On the other hand, the weak structure is expected to suffer from moderate to extensive damage due to low seismic demand, and collapse during the high seismic demand due to insufficient seismic resistance.

Methods of vulnerability analysis vary based on the exposure information and the complexity of the approach. Vulnerability of structures to ground motion effects is often expressed in terms of fragility curves or damage functions that take into account the uncertainties in the seismic demand and capacity. Fragility functions can be developed for buildings or its components depending on how detailed the risk analysis is performed. Early forms of fragility curves were developed as a function of qualitative ground motion intensities largely based on expert opinion. Recent developments in nonlinear structural analysis have enabled development of fragility curves as a function of spectral parameters quantitatively related to the magnitude of ground motion. Fig. 6.a shows the typical seismic demand and structural capacity curves together with their uncertainties expressed in terms of probabilistic distributions. Based on these curves and the associated uncertainties, the fragility curves shown in Fig. 6.b can be constructed for various damage states. Since each damage level is associated with a repair/replacement cost, the probabilistic estimates of the total cost can be estimated using these curves once the hazard is known. This can be achieved by use of predefined representative fragility curves developed for structures in the same class, or custom damage curves developed through nonlinear analysis of individual structures.

Construction of the fragility or damage curves is the key element in estimating the probability of various damage states in buildings or building components as a function of the magnitude of a seismic event. Thus, development of realistic fragility curves for the building stock and lifelines in seismic regions of Turkey constitutes an essential part of a meaningful seismic risk analysis.

3.5. Determination of Seismic Risk and Loss

The standard definition of risk is the probability or likelihood of damage and consequent loss to a given element at risk, over a specified period of time. It is important to note the distinction between risk and vulnerability. Risk combines the expected losses from all levels of hazard severity, also taking their occurrence probability into account, while vulnerability of an element is usually expressed for a given hazard severity level [7]. Loss is defined as the human and financial consequences of damage, including injuries or deaths, the costs of repair, or loss of revenue. The distinction between risk and loss is often very loose and, based on their definition, these terms are sometimes used interchangeably. Since the standard definition of risk is a probability or likelihood of loss, between zero and one, it may be more appropriate to express risk as

$$Risk = Hazard \times Vulnerability \quad (1)$$

while loss depends on the value of the exposure

Soil and Structural Data	Possible analysis and risk assessment studies		
• Location • Construction type • Age • Height and plan area • Occupancy type	Probabilistic risk assessment and loss estimation	Approximate analysis and more reliable risk assessment	Detailed linear/nonlinear analysis, accurate risk assessment and loss estimation
• Column, beam, and wall dimensions • Concrete strength (on site) • Spot check on reinforcement ratio • Average stirrup spacing (modifier)			
• Local soil investigation or detailed soil maps • Structural drawings • Accurate exposure information			

Table 1
Data needed for various levels of analysis and risk assessment.

at risk, given by

$$Loss = Hazard \times Vulnerability \times Exposure \quad (2)$$

Thus, while seismic hazard is purely a product of natural processes, seismic risk and loss are dependent on the vulnerability and societal exposure in terms of the built environment, human population, and value of operations.

4. Seismic Risk Evaluation of a Building Stock and Retrofit Prioritization

Seismic risk assessment of large building stocks can be conducted at various levels depending on the objectives, size of the building stock, available time, and economical constraints. For a rapid and approximate assessment of general seismic risk and probable loss, a rapid visual screening of the building stock is sufficient to gather the necessary data. As the accuracy and reliability of the desired risk assessment study increases, more detailed soil and structural data is necessary to allow for detailed analyses. Table 1 summarizes the site and structural information needed to conduct various levels of seismic risk assessment. In the following subsections, structural evaluation approaches of increasing reliability and complexity are briefly described.

Visual screening leads to a rapid evaluation of building stocks with minimal information requirement, suitable for an overall approximate risk assessment. Such a methodology is reported in FEMA 154 [18], according to which the screened structures are assigned a structural score based on location, structural type, age, height, occupancy type, and visible irregularities. Subsequent risk assessment relies on statistical damage data from previous seismic events for typical building classes. A similar methodology is developed by [19] for buildings in Turkey. This methodology is useful in the sense that it provides a general information about the building stock, identifies buildings requiring priority attention due to serious structural irregularities, and it allows for an approximate risk assessment and loss estimation so that budgetary planning can be conducted in advance. The main disadvantage is that little information can be obtained about the risk of individual buildings since the general risk assessment is based on statistical data.

Approximate analysis requires basic structural information in addition to visual screening methodology such as the dimensions of columns, beams and shear walls, which can be determined from building drawings or measurements, usually on the ground floor. Where building drawings are not available, minimum reinforcement is assumed in the structural elements. Concrete strength is usually assumed a conservative value, however, on site (e.g. Windsor probe) or laboratory measurement of concrete strength is more appropriate for buildings in areas known for variability in material properties. The lateral seismic design loads on the building are calculated using the static equivalent load method and distributed to the floors according to seismic codes. The calculated load demand is compared with the lateral load capacity of the floor determined either individually for each member, or as a whole by simplifying the building system to one of the forms shown in Fig.7. The former requires distribution of the floor load to members according to their rigidities. Evaluation of the building is performed by means of a seismic index, Is, determined by a ratio between the total allowable lateral load and the probable lateral seismic load demand, given by

$$I_s = \frac{V_{all}}{V} \tag{3}$$

This evaluation is generally performed for ground floor only for savings in time and labor. In case it is performed for each floor, the most critical index is assigned for the building. Detailed information on approximate structural evaluation may be found in FEMA [20-23]. A significant advantage of approximate structural evaluation methodologies, other than considerable time savings compared to detailed analysis methods, is the ability to perform a first level prioritization, based on the level of lateral load resistance, for a detailed analysis or retrofit application.

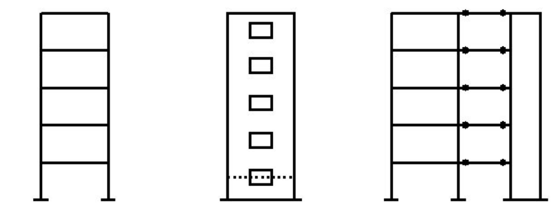


Figure 7. Simplified equivalent building systems for approximate analysis.

Detailed evaluation through linear analysis methods is the most commonly used approach since most seismic codes (e.g.[2, 16]) require use of these methods. Based on detailed structural information, member forces under design loads are determined and compared with their ultimate strength. With this methodology, it is possible to accurately determine the overstressed members under design loads; however, it is difficult to assess the seismic risk of the building at the system level. Thus, although this method is useful in prioritizing deficient structures, it may not yield sufficient information needed for determining the optimum retrofit strategies. The current trend is to use the nonlinear analysis techniques, which require approximately the same amount of data, but more engineering effort and expertise compared to the approaches based on linear analysis techniques.

Detailed evaluation using nonlinear analysis provides the most accurate and reliable risk assessment, loss estimation, and retrofit optimization practices at the expense of detailed site, structural, and material information, longer computation times, and a higher level of technical expertise. The linear analysis methodology described above is an integral part of this methodology. By considering the nonlinear inelastic behavior of structural members under increasing loads, this methodology can predict the nonlinear behavior of the structural system much more realistically compared to linear analysis techniques. Determining the nonlinear structural behavior allows for performance-based design, which results in significant savings in seismic retrofit applica-

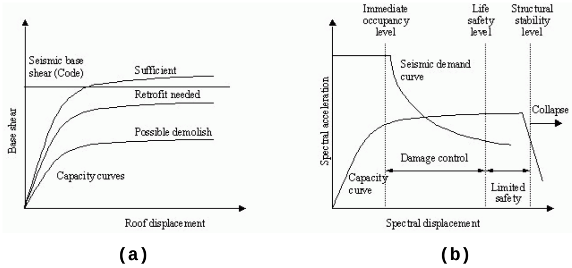


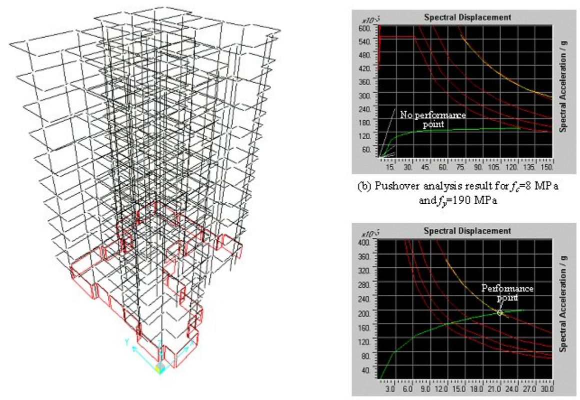
Figure 8. Seismic safety evaluation of buildings using nonlinear analysis (a) evaluation based on equivalent static load (b) evaluation based on performance level.

tions [24, 25, 10]. Fig. 8.a shows the typical roof displacement vs. base shear curve obtained from nonlinear pushover analysis of buildings. Using this curve alone, one can perform a preliminary evaluation of the structure's seismic safety by comparing its capacity with the seismic demand determined using the equivalent static load method described in seismic codes. A better performance evaluation can be performed by converting both the capacity curve and the seismic demand spectrum to the acceleration-displacement response spectrum (ADRS) format formed as a relationship of spectral displacement vs. spectral acceleration as shown in Fig. 8.b. A further improved evaluation can be achieved by obtaining a reduced inelastic response spectrum for the seismic demand to consider the increased damping due to inelastic deformations in the building [24].

The intersection of the capacity and demand curves shown in Fig. 8.b is called the performance point of the building. Based on the location of this performance point, performance level of the building is determined. The intervals of spectral displacement that correspond to different performance levels are also shown in Fig. 8.b. The limits of the performance levels are determined by certain interstory drift values. If the performance point is located in the initial portion of the capacity curve where the inelastic deformations are not significant, which corresponds to interstory drift values less than 0.01, the performance level of the building is immediate occupancy, which is self-explanatory. For interstory drift values between 0.01-0.02, the limits of which are immediate occupancy and life safety levels, respectively, the performance level of the building is damage control. In this region, inelastic deformations are expected in the building that pose no significant threat to the stability of the building and the safety of its occupants. Between the life safety and structural stability levels, the building performance level is described as limited safety. Large inelastic deformations are expected which may result in excessive cracking and failure of some structural members, which may pose threat to occupants or result in local failures. Beyond the structural stability level, the collapse of the building is imminent. From this discussion, it is apparent that nonlinear analysis is a very convenient methodology for development of realistic fragility curves as shown in Fig. 6.b.

Fig. 9 shows an example application of pushover analysis to a ten story building in Istanbul. The structural model of the building is shown in Fig. 9.a. The building was constructed using smooth reinforcing bars, with a design yield strength of 190 MPa, and the concrete strength was conservatively determined as 8 MPa from testing of concrete cores taken from the building. Pushover analysis of the building using these material properties yields the results shown in Fig. 9.b. This figure shows no performance point due to very low lateral load capacity of the building. In its current situation, the building is likely to become heavily damaged or collapse under seismic design loads, and is in urgent need of retrofitting. Fig. 9.c shows the result of a second pushover analysis, which assumes deformed bars with the same size as smooth rebars, and the concrete strength of 20 MPa as specified in the design drawings. In this case, the lateral load capacity of the building is high enough to form a performance point, which indicates a damage control performance level (see Fig. 8.b) and no significant collapse potential. Thus, all other parameters being the same, had deformed bars were used instead of smooth bars as reinforcement, with proper attention to concrete quality, the building would require no intervention to increase its seismic safety. This may be a frequently encountered situation in certain areas, emphasizing the importance of developing realistic fragility curves for risk assessment of large building stocks with high characteristic variability.

The main research challenge regarding seismic evaluation and prioritization of structures is to maximize the accuracy and reliability of the eval-



(a) Structural model of the building

(b) Pushover analysis result for f_c=8 MPa and f_y=190 MPa

(c) Pushover analysis result for f_c=20 MPa and f_y=365 MPa

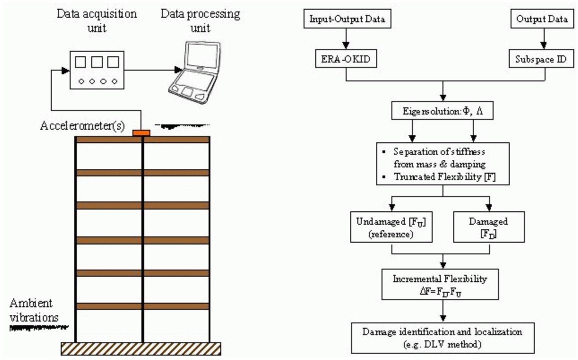
Figure 9. Seismic evaluation of a ten story building using nonlinear pushover analysis.

uation procedure using methodologies as simple as possible. In order to achieve this, there is a need to perform pilot studies that involve both approximate and detailed evaluation of structures to gain insight into the performance of approximate methods and their correlation with the detailed procedures. Nonlinear analysis methods are known to provide the most detailed information about structural performance. However, these methods also suffer from certain drawbacks, which must be well understood and taken into consideration during structural evaluation studies [26, 27]. An important issue regarding use of these methods for buildings with high characteristic variability and inadequate seismic detailing is the assessment of the deformation capacity of structural members. The nonlinear behavior models of structural members must be customized to represent the true behavior of these members for an accurate and reliable evaluation of structural performance.

5. Use of Vibration Techniques in Seismic Risk Assessment

Vibration techniques have long been under research for their potential use in system identification of building systems and identification and localization of structural damage [28]. In seismic risk assessment studies, these techniques may prove effective in performing a rapid, realistic, and cost effective assessment of building characteristics. The method involves measurement of ambient vibrations using sensors and a data acquisition system, and processing of the measured data to obtain dynamic characteristics of the building, such as its vibration frequencies, mode shapes, and stiffness. These determined characteristics, measured at the system level, readily include all material and system variabilities. Determining the actual vibration frequencies of the building not only results in more reliable estimation of seismic design loads, but also allows for a preliminary evaluation of the building by comparing the actual and expected vibration frequencies. A simplified illustration of the application vibration methods to buildings is shown in Fig. 10.a. Accelerometers are placed in the building, usually on the top floor, to measure the acceleration response of the building to ambient effects. Generally, at least three unidirectional accelerometers are used to determine the translational and rotational vibration frequencies in a single experiment. Additional sensors are usually required for more detailed damage identification and localization studies.

A generic flowchart of processing the vibration data for system characterization and damage identification is shown in Fig. 10.b. The methodology to be used in system characterization depends on the availability of input data (ambient effects). When both input and output data are available, the eigensystem realization algorithm with observer Kalman filter (ERA-OKID) [29] method is generally preferred for its robustness. When only the output data is available, which is a more likely case, subspace identification methods based on stochastic approach are utilized [30]. Basic dynamic characteristics of the system are obtained through eigensolution of the frequency and mode shapes. Further information about the system can be extracted through separation of stiffness from mass and damping, and calculation of the truncated flexibility matrix of the system. While system characterization stops here, additional identification and localization of damage requires the truncated flexibility matrices obtained for both undamaged and damaged states. Taking the difference of these matrices, one obtains the incremental flexibility matrix, from which damage identification and localization can be performed using, for instance, the damage locating vector (DLV) method [31, 32]. Provided that a model of the building is available, an iter-



(a) (b)

Figure 10. Vibration techniques for dynamic characterization and damage identification (a) application of vibration techniques (b) generic flowchart of damage identification.

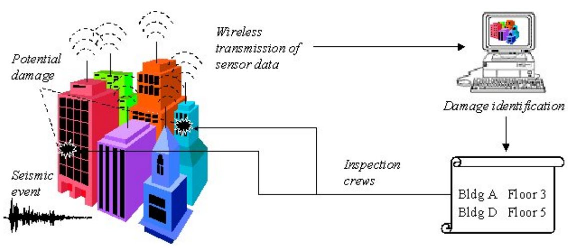


Figure 11. Use of advanced vibration methods for effective health monitoring and emergency management of building stocks.

ative model updating process can be conducted for improved damage identification and localization. The potential benefit of damage identification and localization using vibration techniques is illustrated in Fig. 11. Advances in sensor technology, wireless communication, and fast data processing capabilities, combined with vibration techniques and damage identification/ localization algorithms may lead to continuous/periodic health monitoring of structures and more efficient emergency management after a seismic event.

Applications of vibration techniques and system identification methods lag considerably behind the theoretical developments. Thus, there is a need for laboratory and field implementation of vibration techniques, results of which may be verified and correlated using approximate and detailed analysis procedures. Once established, vibration techniques can effectively be used for approximate system level evaluation of structures as well as for detailed damage identification and localization in continuously monitored structures.

6. A Systems Approach to Large-Scale Seismic Risk Assessment and Hazard Mitigation

For risk assessment and retrofit prioritization of structures in the seismic regions of Turkey, there is an urgent need for a methodology that is rapid, realistic, quantitative, and cost effective. Structural evaluation methodologies reviewed in the previous section display a tradeoff between accuracy and rapidness. Thus, a staged approach may prove to be the optimum solution that results in a rapid and reliable seismic risk assessment that is also cost effective. Stages of such a methodology is shown in Fig. 11. The methodology begins with development of a structural inventory that contains site and structural data sufficient at least to perform an approximate structural analysis (see Table 1). The general building stock is evaluated using approximate structural analyses to determine the seismic index of buildings given by Eq. 3, which allows for a first level prioritization for detailed analysis studies. At this stage, system level dynamic characterization of the buildings can be performed using simple vibration techniques to determine the seismic demand more accurately and to compare the apparent and expected frequencies of the buildings as an approximate indication of their seismic safety. Those buildings with higher priority, i.e. low seismic index are evaluated in detail using nonlinear pushover analysis to determine their lateral load capacity and the performance level. If the performance level is beyond life safety level, in the limited safety range (see Fig. 8.b), then a retrofit decision is made for the building. Optimum retrofit strategy is determined through iterative nonlinear analysis of the structure for various retrofit strategies. For structures at or close to the life safety performance level, the risk of collapse is relatively low. Thus, a risk assessment and loss estimation study can be performed for such structures to make a retrofit decision based on potential level of losses. This methodology allows for a rapid screening of the structural inven-

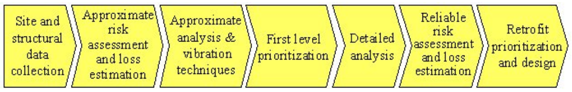


Figure 12. Methodology for Seismic Risk Assessment and Prioritization.

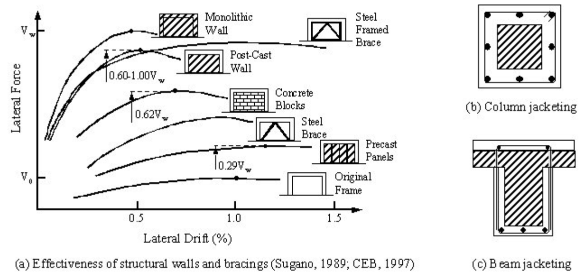


Figure 13. Conventional strengthening methods used for seismic retrofitting.

tory directing attention and resources to structures with high seismic risk in through a cost effective retrofit measure.

It is important to note that the critical and essential structures are given high priority from the very beginning and evaluated in detail using nonlinear analysis methods, skipping approximate analysis and prioritization. The performance criteria for these structures are mainly in the immediate occupancy level, beyond which retrofitting is required.

There is a pressing need for development of an established methodology for seismic risk assessment, prioritization, and hazard reduction of urban infrastructures with high characteristic variability. The presented methodology may form a basis for a more refined and customized methodology, which may be developed through implementations on representative sample of structures in small pilot regions.

7. Methods for Seismic Retrofitting of Structures

Retrofitting of existing structures with insufficient seismic resistance accounts for a major portion of the total cost of hazard mitigation. Thus, it is of critical importance that the structures that need seismic retrofitting are identified correctly, and an optimal retrofitting is conducted in a cost effective fashion. Once the decision is made, seismic retrofitting can be performed through several methods with various objectives such as increasing the load, deformation, and/or energy dissipation capacity of the structure [25]. Conventional as well as emerging retrofit methods are briefly presented in the following subsections.

7.1. Conventional Strengthening Methods

Conventional retrofitting methods include addition of new structural elements to the system and enlarging the existing members [33]. Addition of shear walls and bracings shown in Fig. 13.a is the most popular strengthening method due to its effectiveness, relative ease, and lower overall project cost compared to column and beam jacketing shown in Fig. 13.b and c, respectively. Relative effectiveness of various wall and bracing configurations are compared in Fig. 13.a. From this figure, it is seen that post-cast shear walls and steel braced frames are the most effective strengthening techniques. Although the latter is more effective due to its much higher ductility, post-cast concrete shear walls are the most commonly applied method due to their lower cost and familiarity of the construction industry with the method. Design of additional shear walls is performed to resist a major fraction of the lateral loads likely to act on the structure. This reduces the demand on the beams and columns, hence increasing their safety. Those still likely to be overstressed are strengthened through concrete or steel jacketing, which are relatively more laborious applications. Fig. 14 shows applications of various conventional strengthening methods such as post-cast shear wall (a), additional foundation to support the shear walls to be constructed around the stairs (b), concrete jacketing of a column (c), and addition of column members to remedy vertical irregularities (d). The main research need associated with conventional strengthening methods is optimization of the retrofit design to achieve a satisfactory structural performance level at a minimum cost based on reliably characterized seismic demand and structural capacity.

7.2. Retrofit of Structures Using Innovative Materials

Current research on advanced materials in civil engineering are mainly concentrated on high per-

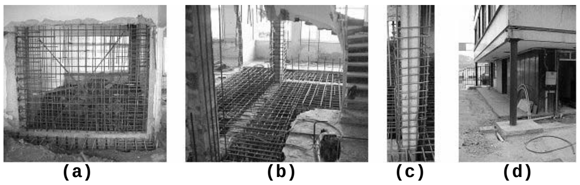


Figure 14. Applications of conventional strengthening methods (a) additional shear wall (b) additional foundations (c) jacketing (d) additional columns.

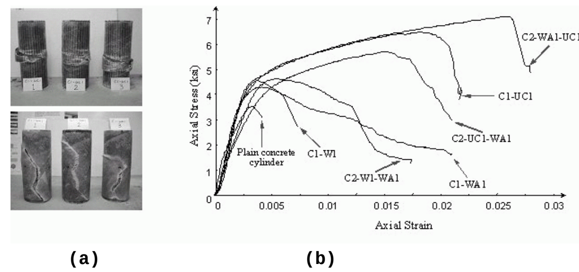


Figure 15. Performance and failure modes concrete cylinders wrapped with FRP composites in various fiber orientations (a) failure modes (b) stress-strain curves of cylinders wrapped in various configurations.

formance concrete and steel, and fiber reinforced plastic (FRP) composites. FRP composite materials have experienced a continuous increase of use in structural strengthening and repair applications around the world in the last fifteen years. High specific stiffness and specific weight combined with superior environmental durability of these materials have made them a competing alternative to the conventional strengthening methods. It was shown through experimental and analytical studies that externally bonded FRP composites can be applied to various structural members including columns, beams, slabs, and walls to improve their structural performance such as stiffness, load carrying capacity, and ductility [34].

FRP composites have enjoyed varying degrees of success in different types of applications. In general, applications that allow complete wrapping of the member with FRP have proven to be effective. Wrapping of columns to increase their load and deformation capacity is the most effective and most commonly used method of retrofitting with composites. However, certain performance and failure mode issues regarding different wrapping configuration and fiber orientations, shown in Fig. 15, still need to be well understood [35]. When wrapping is difficult or not allowed, such as when strengthening beams, slabs, or walls, success of the method is sometimes hindered by premature debonding failures [36]. Fig. 16 shows the performance of beams strengthened using pultruded FRP plates in various configurations. It can be seen from this figure that flexural strengthening of beams without proper attention to brittle shear and debonding failure modes not only renders the strengthening application ineffective, but also harms the member by decreasing its ductility. This constitutes one of the main factors, along with their high material costs, hindering wide-range use of FRP materials [37, 36]. Such problems can be reduced through proper design and anchorage of the external FRP reinforcement [38, 39, 40]. Thus, decision makers must approach using these materials with caution and must ensure that the design is performed with adequate knowledge and skill, and verified through laboratory testing.

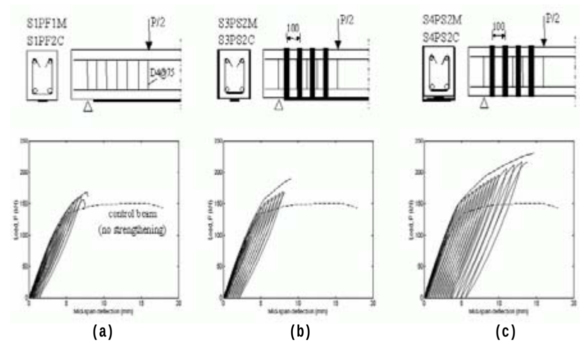


Figure 16. Influence of shear strengthening and anchorage on FRP strengthened beam behavior under cyclic loading (a) flexural (b) flexural + shear (c) flexural + shear + anchorage.

Limited research and applications regarding seismic retrofitting of building systems with FRP composites have shown that composites retrofitting does not significantly alter the stiffness and dynamic properties of the building. The main benefit of retrofitting with composites is the

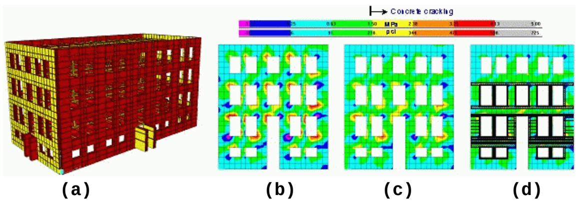


Figure 17. A retrofit application combining conventional and composites retrofitting (a) 3-D building model (b) wall stresses (c) after installation of (d) additional FRP before retrofitting steel window frames retrofitting.

increase in deformation capacity of the building, and in its load capacity to an extent. This may achieve the retrofit objectives for buildings with lightly insufficient seismic resistance. For buildings with large seismic deficiencies, a combination of conventional and FRP strengthening techniques may prove to be an effective retrofitting solution. Fig. 17 shows such an application where a historical school building in Istanbul was retrofitted using steel and FRP composites. The 3-D computer model of the building is shown in Fig. 17.a, the analysis of which revealed that under seismic design loads excessive cracking is expected around the openings in the exterior unreinforced concrete walls in the short direction due to stress concentrations as shown in Fig. 17.b. As a practical and economical solution, the retrofit design involved replacement of the existing window frames with structural steel frames constructed from steel C-sections. A verification analysis of the retrofitted building showed that installation of steel window frames largely decreased the stress concentrations, but did not suffice to reduce all stresses to acceptable levels. For this reason, additional retrofitting was designed using externally bonded FRP composites around the openings in the walls to prevent or delay concrete crack propagation by bridging the stresses at crack locations. Thus, by combining conventional and innovative materials, an effective and economical retrofit design was achieved that did not significantly interfere with the function or historical and architectural character of the building.

FRP composites are widely recognized for their potential use in seismic retrofitting applications. To achieve wide-range use of these materials, however, there is need for further research into a number of issues related to mechanics, design, and durability of FRP retrofitted concrete and steel systems. Despite considerable progress in these areas since early last decade [41], further improvements are necessary to meet the needs of the retrofit industry. Failure mechanisms, with emphasis on brittle shear and debonding failures, must be thoroughly understood and associated design procedures must be incorporated in design codes. Influence of cyclic and fatigue loading on the FRP strengthened member performance must be characterized and accounted for in the design process. Although FRP composites are known for their favorable durability characteristics, only limited information is available on long-term durability and performance of FRP bonded concrete and steel systems. These issues need to be investigated through accelerated test studies and related design, application and protection requirements must be included in the design codes.

7.3. Base Isolation

The seismic base isolation technology involves placing flexible isolation systems between the foundation and the superstructure. By means of their flexibility and energy absorption capability, the isolation systems reflect and absorb part of the earthquake input energy before this energy is fully transmitted to the superstructure, reducing the energy dissipation demand on the superstructure. Base isolation causes the natural period of the structure to increase and results in increased displacements across the isolation level and reduced accelerations and displacements in the superstructure during an earthquake. This not only provides safety against collapse, but also largely reduces damage, which is crucial for facilities that should remain operational after severe earthquakes such as emergency response centers, hospitals, and fire stations [42-47]. Base isolation can also be used in seismic retrofitting of historic structures without impairing their architectural characteristics by reducing the induced seismic forces. Fig. 18 shows the results of a feasibility study for base isolation of a historical school building in Istanbul [48]. The structural system of the building is formed by thick exterior unreinforced concrete walls resisting lateral loads and interior steel frames carrying the vertical loads. A combination of lead-plug rubber bearings and natural rubber bearings were

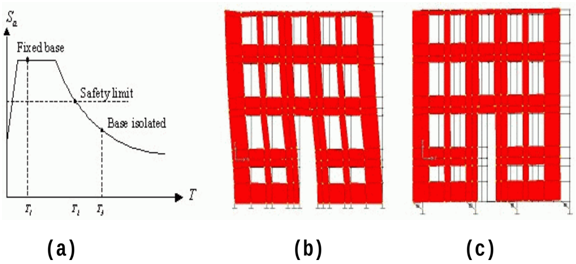


Figure 18. Analysis and design of building base isolation (a) design of base isolation (b) deformations before base isolation (c) after base isolation.

considered for the exterior walls and the interior frames, respectively. The basic design philosophy shown in (a) is to increase the fundamental period of the structure so that the effective seismic demand on the structure is less than that can safely be resisted by the structure. Analysis results showing the deformed shape of the building before and after the base isolation in (b) and (c), respectively, make it clear that base isolation reduces the deformations and hence the stresses in the building.

Base isolation is generally suitable for low to medium rise buildings, usually up to 10-12 stories high, which have their fundamental frequencies in the range of expected dominant frequencies of earthquakes. Superstructure characteristics such as height, width, aspect ratio, and stiffness are important in determining the applicability and effectiveness of seismic isolation. The seismicity of the region and the underlying soil conditions should also be considered in the feasibility studies and design process. Base isolation should be avoided in areas where expected fundamental frequencies of the earthquakes are in the lower frequency domain or on soft soil sites where amplification of low earthquake frequencies may occur. One other constraint in the application of base isolation is the large relative displacements between the superstructure and the supporting ground at the isolation level. A clearance around the building must be provided and maintained through the life of the structure to accommodate the expected large displacements. Such displacements may be reduced with the incorporation of additional stiffness and energy dissipation mechanisms in the isolation system.

The International Building Code [16] and FEMA 356 [25] specify the methodologies according to which seismically isolated structures can be designed. Both the isolation system and the isolated structure are required to be designed to resist the deformation and stresses produced by seismic events. Two levels of earthquake input are considered in design. The design earthquake (475-year return period) is used to calculate the total design displacement of the isolation system and the lateral forces and displacements of the isolated structure, and the maximum considered earthquake (1000-year return period) is used to calculate the total maximum displacement of the isolation system to ensure its integrity even at extreme ground shaking. Deformation characteristics of the isolation system is required to be based on properly substantiated prototype tests with predefined sequence and number of loading cycles.

Seismic isolation is proven to be a very effective method for protecting buildings and other structures against seismic hazards [45, 49, 47]. An important disadvantage of the method, however, is that it cannot be applied partially to structures, unlike most other seismic retrofitting methods. For this reason, the cost of base isolation is often significantly higher than alternative retrofitting methods. This often limits the application of base isolation to (1) special buildings, such as certain industrial, research, public and hospital buildings that contain sensitive equipment or strict operational and performance requirements, (2) historical buildings, the architectural and historic character of which may be harmed by alternative retrofitting methods, (3) bridges, for which relatively less number of isolators are required and installation is easier. In order to increase the cost competitiveness of base isolation for buildings, there is need for research in the areas of reducing the application costs through efficient design and specialized equipment, and optimization of isolator types, combination, and arrangement.

7.4. Supplemental Energy Dissipation and Structural Control

An alternative and often more cost efficient retrofitting strategy compared to base isolation is installation of supplemental energy dissipation devices in structures as a means for passive or active structural control [50-55,25]. The objective of structural control is to reduce structural

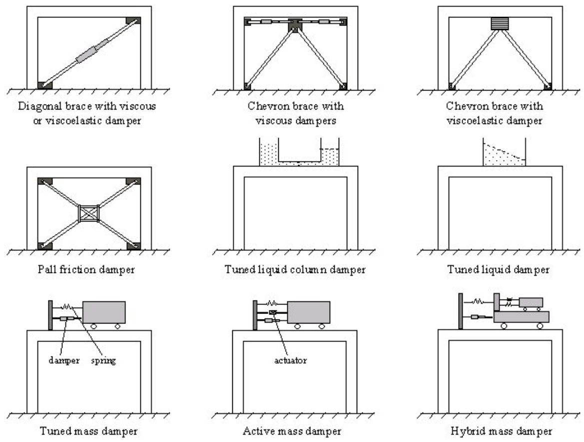


Figure 19. Supplemental energy dissipation devices.

vibrations for improved safety and/or serviceability under wind and earthquake loadings. Passive control systems reduce structural vibration and associated forces through energy dissipation devices that do not require external power. These devices utilize the motion of the structure to develop counteracting control forces and absorb a portion of the input seismic energy. Active control systems, however, enhance structural response through control forces developed by force delivery devices that rely on external power to operate. The actuator forces are controlled by real time controllers that process the information obtained from sensors within the structure. Semi-active control systems combine passive and active control devices and are sometimes used to optimize the structural performance with minimal external power requirements. Fig. 19 shows the basic principles of various control systems commonly used to control wind and seismic forces acting on building structures.

The severity of seismic demand on a structure is proportional to its stiffness and inversely proportional to its damping or energy dissipation capacity. Thus, installing supplemental energy dissipating devices in the structure reduces the seismic demand and results in increased safety of the structure and its contents from the damaging effects of earthquakes. In recent years, considerable attention has been paid to research and development of structural control devices, with particular emphasis on improving wind and seismic response of buildings and bridges. In both areas, efforts have been made to develop the structural control concept into a workable technology, and as a result, such devices have been installed in a variety of structures around the world. The most challenging aspect of vibration control research in civil engineering is the fact that this is a field that requires integration of a number of diverse disciplines, some of which are not within the domain of traditional civil engineering. These include computer science, data processing, control theory, material science, sensing technology, as well as stochastic processes, structural dynamics, and wind and earthquake engineering. These coordinated efforts have facilitated collaborative research among researchers from a diverse background and have accelerated the research to the implementation process. Continued research is essential in this area to develop effective and affordable retrofitting solutions for structures with insufficient seismic resistance.

A special concern regarding the use of energy dissipation devices in structures with high characteristic variability is the fact that the effectiveness of such devices is dependent on the deformation capacity of the structure. For structures that suffer from inadequate seismic detailing, which translates into insufficient deformation capacity, great caution must be exercised in use of these devices for seismic retrofitting. A feasible solution may be to combine this technique with deformation enhancement measures to ensure their effectiveness. This constitutes an important research area with valuable potential contribution and high potential benefits.

7.5. Effects of Seismic Retrofitting on Structural Performance

The seismic retrofit techniques briefly presented in the preceding sections vary in the mechanisms that they decrease the seismic risk of structures [24] Fig. 20 graphically illustrates these mechanisms by means of their effects on the seismic demand and structural capacity curves shown in Fig. 8. These effects are presented in the following paragraphs at a simplified conceptual level.

The typical effect of conventional strengthening methods is shown in Fig. 20.a. Conventional strengthening applications generally lead to an increase in both the stiffness and the lateral load capacity of the structure. This is shown

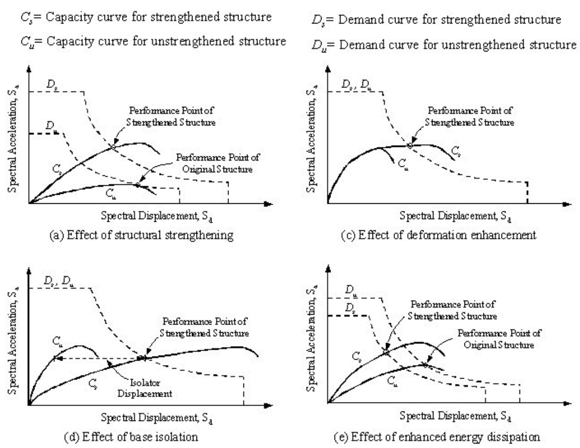


Figure 20. Effects of various retrofit measures on structural performance.

by the capacity curve of the strengthened structure, C_s, which has a higher slope and peak compared to the capacity curve before strengthening, C_u. Due to the increased stiffness, which translates into a decreased fundamental period, the seismic demand on the structure is also increased, as shown by the demand curve for the strengthened structure, D_s, compared to that for the unstrengthened structure, D_u. Although the capacity increase is partly alleviated by the increase in seismic demand, the overall performance of the structure is improved as shown by the locations of the performance points on the spectral displacement axis for before and after strengthening. Increasing the overall deformation capacity of a structure is also an effective seismic retrofitting method. Insufficient deformation capacity of structural members is usually increased through various measures such as providing additional confinement by additional stirrups or wrapping with FRP composites. Fig. 20.b shows the effect of deformation or ductility enhancement on the structural performance. While the capacity curve of the structure prior to retrofitting does not intersect the demand curve, an intersection i.e. a performance point is obtained after retrofitting. It is important to note that since the stiffness and damping characteristics of the structure are not significantly altered, the demand curve remains essentially the same after retrofitting.

The effectiveness of seismic base isolation in increasing the structural performance during seismic events is shown in Fig. 20.c. Base isolation significantly increases the effective fundamental period and deformation capacity of the structure. This is apparent from the capacity curve of the base isolated structure, C_s, shown in Fig. 20.c. It seems somewhat contradictory, however, that the demand curve for the base isolated structure, D_s, is shows as higher than the fixed-base condition, D_u, since base isolation is known to decrease the seismic demand on the structure. This is due to the fact that the energy dissipation in a base isolated structure is significantly different than the same structure in fixed-base condition. Due to relatively lower stiffness of the isolation system, the effective damping for a certain spectral displacement is lower in the base isolated structure, resulting in a higher apparent seismic demand. However, since the deformation capacity of the structure is significantly increased, a major portion of which taking place at the isolation level, the building can safely tolerate this apparent increase in the seismic demand, resulting in a satisfactory performance level.

Seismic retrofitting of structures using energy dissipation devices such as those shown in Fig. 19 result in an increase in the stiffness, load capacity, and effective damping of the structures. Effects of these on the structural performance is shown in Fig. 20.d. As can be seen from the figure, the effect of energy dissipation devices on the capacity curve is similar to structural strengthening with conventional methods shown in Fig. 20.a. Additional advantage of using energy dissipation devices is that the seismic demand on the structure is also reduced due to increase in the effective damping of the structure. Comparing the seismic demand curves before (D_u) and after (D_s) retrofitting in Fig. 20.a and d, it is apparent that use of energy dissipation devices results in a more desired performance level compared to conventional strengthening methods.

Selection of a particular retrofitting technique depends on the seismic demand, structural capacity, the required performance level, functional characteristics and the importance of the structure. The main challenge is to achieve a desired performance level at a minimum cost, which can best be achieved through a detailed nonlinear analysis as demonstrated by Fig. 8 and the above discussions. Ideally, each structure must be evaluated in detail to determine the optimum retrofit strategy compatible with its characteristic. In the case of large building stocks, however, a classification of structures according to their current and required performance levels may lead to development of common standardized retrofit strategies for structures in the same group, which in turn may prove to be a more rapid and cost effective overall methodology.

8. A Futuristic Vision: e-quake

Recent advances in computational resources and processing techniques have opened up new horizons for effective risk assessment, hazard mitigation, and emergency management of existing infrastructures in urban areas. A research initiative at the Massachusetts Institute of Technology (M.I.T.) deals with large-scale disaster management in urban areas with current focus on earthquake impact simulation by means of a prototype information system called e-quake [56]. The objective of the e-quake system is to simulate a city's response to an earthquake by generating digital models of urban infrastructure. The system framework includes integration of information management, advanced modeling of physical systems, and decision-making. Through management of information from multiple heterogeneous data sources (e.g. geographical, geological, seismological, exposure, material, social, and human-physical interaction data), e-quake is expected to provide a comprehensive understanding of the interactions between components of the complex dynamic urban infrastructure system.

The main thrust areas of the e-quake system include modern information technology (IT), computational analysis of complex dynamic systems, and decision making/strategic emergency management. Role of information technology in the general area of urban disaster and emergency management is shown in Fig. 21. The IT component of the e-quake system includes integration of modern database technology to create a three-dimensional virtual model of the city in different layers that include hazard information and site conditions, structures, utilities and lifelines, their interactions, and population. A central challenge in building a digital model of a city is the problem of managing the decision support services and their vast amounts of associated information, some of which is certain to be incomplete. While geographic information systems are becoming empowered by new standards for interoperability over the web and advances in global positioning system (GPS) technology, e-quake promises to even further empower information systems of the future. These include advances in wavelet techniques, which permit user interaction with compressed data streams and the multi-scale representation of 3D geometry, as well as the evolution of object relational database management systems to support core services such as finite element (FE) simulations.

In managing the large-scale heterogeneous data, e-quake will operate as a mediator. E-quake will query, monitor, transform, combine and locate desired information between the heterogeneous set of applications and data sources. External sources like the HAZUS earthquake loss estimation methodology and its GIS database that provides physical and social data in the form of 2D layers as well as CAD data files with specific exchange file formats have to be processed, analyzed and synthesized by domain-specific database operators. Since mediators understand application technology as well as database terminology, e-quake will be able to combine, and take advantage of both high-level domain-specific data interaction and efficient data management. Fig. 22 shows the interaction of the e-quake simulator with various integrated key modules.

Computational analysis capabilities of e-quake include modeling of seismic wave propagation in infinite soil domains and finite structures for accurate seismic demand characterization, a complete description of all conceivable failure modes of the city at the geotechnical and structural level, and multi-scale analysis of the defined system using efficient wavelet or finite element methods. Instead of transferring data to FE applications, almost all functions of modern computational analysis are executed within the database. The state of the art is set out by finite element programs that model wave propagation in solids, contact and friction problems, and that predict the failure on both material and structure level. In addition to these standard functions of a finite element analysis code, a multi-scale resolution algorithm will be established. Thus, the mechanical response, represented by a time dependent displacement field, is given at different levels of accuracy. An e-quake simulation can produce a

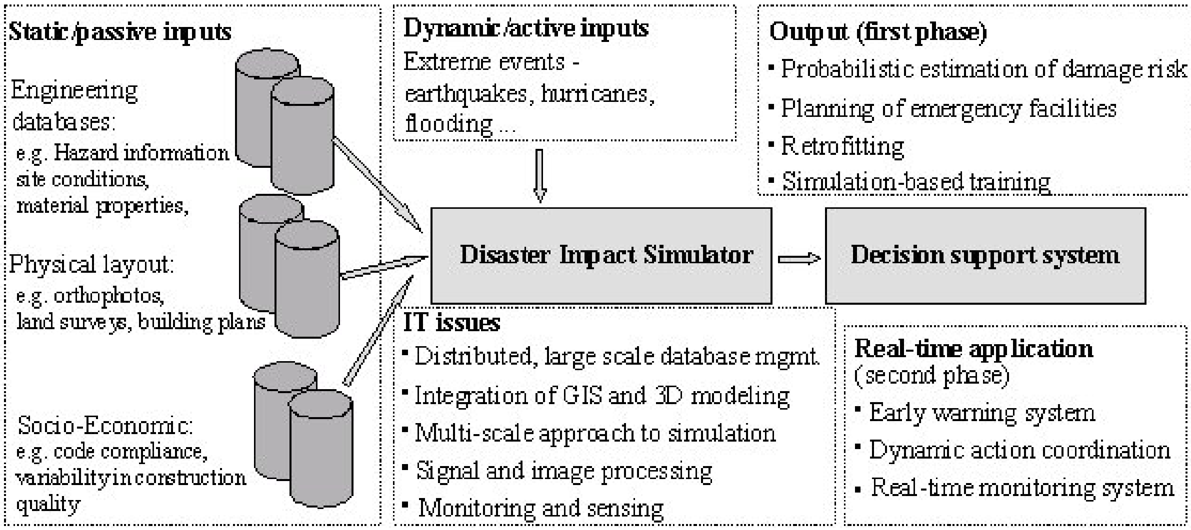


Figure 21. Role of information technology in disaster and emergency management.

first approximation of the city's response as well as detailed information about local damage. E-quake's high computational performance results from the modern database system. Managing the whole input data, the object-oriented database system will contain the FE-analysis kernels in the form of a function that operates directly on the database. Time consuming read and write operations will be reduced. In addition, parallelization concepts for CPU intensive operation within the database will be developed. Both integrated program kernels and the parallelization concept will lead to a database system with an extremely high computational performance.

The summary key benefits of the e-quake system will be: (1) generate the core technology for future decision making based on management of a distributed database system with heterogeneous data, (2) mechanical analysis of urban environments subjected to catastrophic events, (3) unique visualization possibilities such as walk through a virtually damaged city, (4) integrated communication technology that permits virtual expert meetings and virtual site visits, (5) integrated loss estimation capabilities and assistance in optimized retrofit strategies.

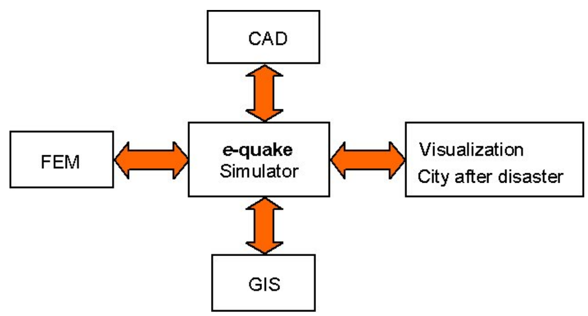


Figure 22. Data exchange and flow in the e-quake simulator.

9. Conclusions

Seismic risk assessment and hazard reduction of urban infrastructures and population located in seismic regions is a challenge faced by numerous countries around the world. The challenge is relatively less pronounced for developed countries in which preparedness and mitigation activities have been well under way, although the Northridge and Kobe earthquakes have shown that even the most prepared are vulnerable to seismic hazards. The significance of the challenge and the size of potential destruction are far more pronounced for developing countries, the existing infrastructures of which are known for their variability in seismic resistance and quality of construction. The anticipation of a major earthquake in the Istanbul area in Turkey raises dire concerns about potential size of damage and loss in this densely populated region with a large inventory of structures, lifelines, industrial and storage facilities, and utility systems. The size of the problem and the time constraint presses for adoption and further development of a systems approach that may lead to an effective, rapid, and economical evaluation and mitigation methodology.

In this paper, the components of a large-scale seismic risk assessment and hazard reduction methodology is presented including the recent state of the art developments and continued research needs. The key components of the overall methodology can be expressed in general terms as (a) characterization of seismic demand, (b) characterization of structural vulnerability, (c) optimized retrofitting of structures to meet the required performance levels. Each of these areas contains several opportunities for collaborative research activities.

In the area of seismic demand characterization, development and maintenance of a database that contains information about the seismic source characteristics, geology, and seismicity of priority regions is necessary. An initiative to develop a detailed hazard map combined with microzonation studies that reveal detailed site specific information regarding soil amplification, liquefaction, and ground failure potentials, supported by GIS capabilities would be highly beneficial in accurate seismic demand characterization.

A realistic determination of the seismic vulnerability of the structural inventory in seismic regions is the central component of a successful risk assessment and hazard reduction efforts. The initial step in such efforts is the development of a structural inventory to establish the exposure information. Construction of characteristic fragility curves for typical structural categories may be performed through pilot studies in small representative areas. The primary research goal in this area is rapid screening and prioritization of structures for seismic retrofit. For this purpose, the presented systems approach (see Fig. 12) may form the basis for a refined and customized overall strategy, especially in view of the high variability in structural characteristics. Exploration of vibration techniques may prove to be useful in rapid characterization of buildings at system level. Further research into advanced vibration techniques could lead to development of an efficient emergency management and response strategy.

Retrofitting of structures with insufficient seismic resistance constitutes the most expensive component of hazard mitigation efforts. Thus, accurate identification of structures that are in need of seismic retrofitting, and optimization of the retrofit applications to achieve the required structural performance levels at minimum cost are critical economical issues. These issues are dependent on the accuracy of seismic demand and vulnerability characterizations to a large extent. Research into evaluation of available conventional and innovative retrofit options, with attention to application specific issues as listed in respective sections, is deemed essential. Recent advances in computational resources, database management, geographic information systems, sensor technology, and efficient visualization techniques allow for futuristic visions such as simulating the impact of an earthquake at the scale of a city. The e-quake research initiative at M.I.T. envisions simulating a city's response to an earthquake by generating digital models of its urban infrastructure. Key challenges of the e-quake system are management of information from multiple heterogeneous resources, and modeling of the interactions between components of the complex dynamic urban infrastructure system. Although realization of such a system may be a long-term objective, it is meritorious for establishing a research framework with well-defined collaborative research issues. Addressing these issues at the present time will undoubtedly serve the development of future large-scale impact simulation systems that will lead to more effective seismic risk assessment, hazard reduction, and emergency management practices.

10. Acknowledgements

Parts of the work reported in this paper were supported by the National Science Foundation under Grant No 0010126 to Massachusetts Institute of Technology, Cambridge, MA. The authors thank Erdem Karaca, a graduate student in the Civil and Environmental Engineering Department at M.I.T., for his assistance with the preparation of this paper.

References

[1] T. Parsons, S. Toda, R. Stein, A. Barka, and J.H. Dieterich, Bilim ve Teknik, **390**, 90 (2000).

[2] TC-BIB, Specification for Structures to be Built in Disaster Areas, (Ministry of Public Works and Settlement, Ankara, Turkey, 1998).

[3] UDK, Deprem Zararlarını Azaltma Ulusal Stratejisi, (Ulusal Deprem Konseyi, Ankara, Turkey, 2002).

[4] DIE, Bina Sayımı 2000 (T.C. Başbakanlık Devlet İstatistik Enstitüsü://www.die.gov.tr/konular/insaat.htm, 2000).

[5] TC-BIB, Specification for Structures to be Built in Disaster Areas, (Ministry of Public Works and Settlement, Ankara, Turkey, 1975).

[6] EERI, Earthquake Spectra **13**, 4 (1997).

[7] A.W. Coburn, R.J.S. Sspence, and A. Pomonis, Vulnerability and Risk Assessment, Disaster Management Training Programme (DMTP) of the United Nations Development Programme (UNDP), (Cambridge Architectural Research Limited, Cambridge, UK, 1994).

[8] CSSC, Earthquake Risk Management: A Toolkit for Decision-Makers, California Seismic Safety Commission, (CSSC Report 99-04, Sacramento, CA 1999).

[9] A.M. Chandler and T.K.L. Nelson, Engineering Structures **23**, 1525 (2001).

[10] F. Bendimerad, Soil Dynamics and Earthquake Engineering **21**, 67 (2001).

[11] FEMA, Estimating Losses From Future Earthquakes, Panel Report, (Washington, D.C, 1989).

[12] S. L. Kramer, Geotechnical Earthquake Engineering (Prentice Hall, NJ, 1996).

[13] A. Marcellini, R. Daminelli, G. Franceschina, and M. Pagani, Soil Dynamics and Earthquake Engineering, **21**, 415 (2001).

[14] A. Frankel, S. Hartzell, and E. Şafak, Assessment of Seismic Hazard at Ford-Otosan Plant in Gölcük, Turkey, (U.S. Geological Survey, Geol. Hazards Team (CO,1999).

[15] FEMA, HAZUS 99 Technical Manual (Washington, D.C, 1999).

[16] IBC, Int. Code Council, Falls Church (VA, 2000).

[17] ATC, Earthquake Damage Evaluation Data for California, ATC-13 (Redwood City, California, 1985).

[18] FEMA , Rapid Visual Screening of Buildings for Potential Seismic Hazards: A Handbook (Washington, D.C, 1988).

[19] P. Gülkan, A. Yakut, H. Sucuoğlu, M. S. Yücemen, and E. Cıtıpıtıoğlu, A Seismic Damage Assessment Form for Engineered Construction, Earthquake Engineering Research Center Report No: 94.01 (Middle East Technical University, Ankara, Turkey, 1994).

[20] FEMA, NEHRP Handbook for the Seismic Evaluation of Existing Buildings (Washington, D.C, 1992).

[21] FEMA, Handbook for the Seismic Evaluation of Buildings-A Prestandard (Washington, D.C, 1998).

[22] A.S. Scarlat, Approximate Methods in Structural Seismic Design (E&FN Spon, London 1996).

[23] M. Hawkins (Ed.), Seismic Design for Existing Structures, ACI-SCM-14, (American Concrete Institute (MI, 1986).

[24] ATC, Seismic Evaluation and Retrofit of Concrete Buildings, ATC-40 (Redwood City, California, 1996).

[25] FEMA, Prestandard and Commentary for the Seismic Rehabilitation of Buildings, (Washington, D.C, 2000).

[26] H. Krawinkler and G. D. P. K. Seneviratna, Engineering Structures, **20**, 4 (1997).

[27] A. Ghobarah, Progress in Structural Engineering and Materials **2**, 60 (2000).

[28] S. W. Doebling, C. R. Farrar, and M. B. Prime, The Shock and Vibration Digest **30**, 2 (1998).

[29] J. N. Juang, Applied System Identification (Prentice-Hall, NJ, 1994).

[30] Bernal and O. Güneş, Damage localization in output-only systems: A flexibility based approach (Proceedings of IMAC-XX: A Conference & Exposition on Structural Dynamics, Los Angeles, California, 2002).

[31] Bernal, Journal of Engineering Mechanics **128**, 1 (2002).

[32] B. Güneş, Ph.D. Thesis, Northeastern University (2001).

[33] A. Newman, Structural Renovation of Buildings (McGraw-Hill, New York, NY, 2001).

[34] O. Büyüköztürk and B. Hearing, ASCE Journal of Composites in Construction **2**, 138 (1998).

[35] C. Au, M.S. Thesis, Massachusetts Institute of Technology (2001).

[36] O. Güneş, Ph.D. Thesis, Massachusetts Institute of Technology (2002).

[37] O. Büyüköztürk, B.Hearing, and O. Güneş, FRP Strengthening and Repair: Where do we go from here?, Structural Faults and Repair 99 (M. C. Forde (Ed), London, UK, 1999).

[38] O. Büyüköztürk, O. Güneş, and E. Karaca, to appear in Journal of Construction and Building Materials (2002).

[39] O. Büyüköztürk, O. Güneş, and E. Karaca, (ASCE Engineering Mechanics Conference, Columbia University, NY, June 2-5 (2002).

[40] O. Büyüköztürk, O. Güneş, and E. Karaca (Proceedings of the Seventh U.S. National Conference on Earthquake Engineering, Boston, MA, July 21-25, 2002).

[41] ACI-440F, Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures (ACI Committee 440-F Report, American Concrete Institute Detroit, 2000).

[42] EERI, Earthquake Spectra **6**, 2 (1990).

[43] ATC, Proceedings of Seminar on Seismic Isolation, Passive Energy Dissipation, and Active Control, ATC-17 (Redwood City, California, 1993).

[44] J. M. Kelly, Earthquake Resistant Design with Rubber (Springer, 1993).

[45] R. I. Skinner, W. H. Robinson, and G. H. McVerry, An Introduction to Seismic Isolation, John Wiley & Sons (1993).

[46] J. J. Connor and B. S. A. Klink, Introduction to Motion Based Design, Computational Mechanics Publications (1996).

[47] P. Komodromos, Seismic Isolation for Earthquake Resistant Structures, WIT Press, Boston, MA (2001).

[48] N. Bachas, L. Duenas, J. P. Kelly, and T. Wu, The Rehabilitation of Mitchell Hall for Seismic Upgrade, Master of Engineering project report, Massachusetts Institution of Technology, Department of Civil and Environmental Engineering, Cambridge, MA (2001).

[49] Y. Kitagawa and M. Midorikawa, Smart Materials and Structures, **7**, 581 (1998).

[50] G. W. Housner, L. A. Bergman, T. K. Caughey, A. G. Chassiakos, R. O. Claus, S. F. Masri, R. E. Skelton, T. T. Soong, B. F. Spencer, and J. T. P. Yao, Journal of Engineering Mechanics **123**, 9 (1997).

[51] EERI, Earthquake Spectra **9**, 3 (1993).

[52] M. C. Constantinou, and M. D. Symans, J. of Structural Design of Tall buildings **2**, 77 (1993).

[53] M. D. Symans and M. C. Constantinou, Engineering Structures **21**, 469 (1999).

[54] T. T. Soong, Active Structural Control: Theory and Practice (Longman Scientific and Technical, New York, 1990).

[55] T. T. Soong and G. F. Dargush, Passive Energy Dissipation Systems in Structural Engineering (John Wiley & Sons, New York, 1997).

[56] O. Büyüköztürk, J. J. Connor, F. J. Ulm, K. Amaratunga, O. Güneş, E. Karaca, and D. Mohr, E-Quake Earthquake Impact Simulator, Internal Research Report, Massachusetts Institute of Technology, Department of Civil and Env. Engineering, Cambridge, MA (2000).